

PROBING THE NATURE OF SEISMIC DISCONTINUITIES IN THE EARTH'S MANTLE WITH SYNCHROTRON X-RAY BEAMS

In this endeavor to better understand Earth's mantle, a laser-heated diamond anvil cell was employed at the GSECARS undulator beamline at the Advanced Photon Source in order to observe the phase transformation in Mg_2SiO_4 from its spinel form (ringwoodite) to a mixture of MgSiO_3 (perovskite structure) and MgO (rocksalt structure). These measurements provide the first direct evidence for the occurrence of this “post-spinel” transformation at the appropriate pressures and temperatures for the major seismic feature of the Earth's mantle—the 660-km discontinuity.

Recent developments in synchrotron-based high-pressure experiments allow us to investigate the nature of materials directly under the extreme pressure and temperature conditions that exist within deep planetary interiors. Using the laser-heated diamond anvil cell at the GSECARS sector of the Advanced Photon Source, we have investigated the phase transformation in Mg_2SiO_4 from its spinel form (ringwoodite) to a mixture of MgSiO_3 (perovskite structure) and MgO (rocksalt structure). For the first time, this “post-spinel” transformation was directly observed to occur at the appropriate pressures and temperatures for the major seismic feature of the Earth's mantle—the 660-km discontinuity. The identification of an isochemical phase transition with the 660-km discontinuity (as opposed to a chemical change) favors models for mantle dynamics that allow for extensive mixing of material from the crust to the core. In such a model, the ultimate resting place for the oceanic crust, which plunges beneath the Earth's surface in places such as Japan and the Andes, may be 2900 km below the surface on top of the molten metal core.

The nature of the Earth's deep interior is most effectively probed by using seismic waves generated during earthquakes and recorded at seismic monitoring stations all over the globe. Geophysicists are interested in exploring fundamental questions about the Earth's mantle, such as its evolution over geo-

logical history and its relation to the mantles of other rocky planets such as Mars and Venus. One of the most prominent seismic features of our planet's mantle is an abrupt 6% increase in the speed of seismic waves that is observed near a depth of 660 km. This “660-km discontinuity” has been of fundamental interest for more than a generation because of its recognized importance in determining the degree of intermixing in the Earth's mantle. Does this discontinuity represent a compositional boundary in a chemically and dynamically stratified Earth, or is it due to a phase transformation in a more homogeneous body? The answer to this question affects our understanding of many phenomena, ranging from the Earth's present thermal structure to our notion

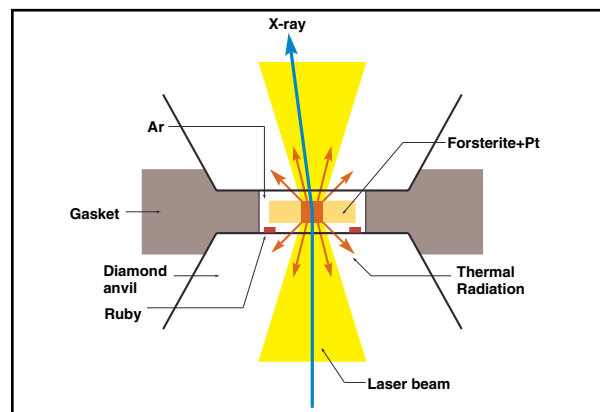


FIG. 1. Schematic illustration of the laser-heated diamond anvil cell. The diameter of the flat surface of the diamond is about 0.3 mm and the diameter of the sample chamber is typically 0.15 mm.

of how the planet's basic building blocks were assembled four and a half billion years ago.

To reproduce the conditions of the deep mantle, the laser-heated diamond anvil cell is used (Fig. 1). In this device, the sample is compressed between two gem-quality diamonds (typically ~ 0.25 carat). The sample is placed in a small hole in a metal foil held between the diamonds. Pressure is increased by advancing a set of screws that applies force to the diamonds. While at high pressures, the sample is simultaneously heated on both sides using an infrared laser. The laser-heating system at GSECARS, which is the most advanced in the world, also allows for simultaneous measurement of the two temperature profiles using spectroradiometry. Argon was also loaded into the sample chamber to thermally insulate the sample from the high-thermal-conductivity diamond anvils. The diamond cell has two major advantages for high-pressure studies: (1) the achievable pressure range encompasses that of the entire Earth's mantle and (2) diamonds are transparent across large portions of the electromagnetic spectrum, including portions of the infrared and the hard (>10 keV) x-ray region. The principal limitation of the diamond cell is that only small sample volumes can be subjected to deep mantle conditions. At conditions corresponding to 660-km depth (2000 K and 24 GPa, which is equivalent to 240,000 bar), the amount of material at simultaneous high pressure-temperature (P-T) conditions is about 10 ng. Thus, the use of radiation from a third-generation synchrotron source is essential for this work.

The mineral olivine, Mg_2SiO_4 , is an important component of mantle-derived rocks, and transformations involving this phase have long been considered to be candidates for the 660-km discontinuity. However, direct proof was lacking and there have been some recent suggestions that transformations in this material did not occur at the appropriate conditions to be responsible for the discontinuity. To investigate this, we compressed a mixture of pure forsterite powder with platinum metal in a diamond cell. The latter serves both to absorb the infrared laser beam and as a pressure calibrant (based on shock-wave data). Olivine is known to undergo a sequence of phase transformations with pressure,

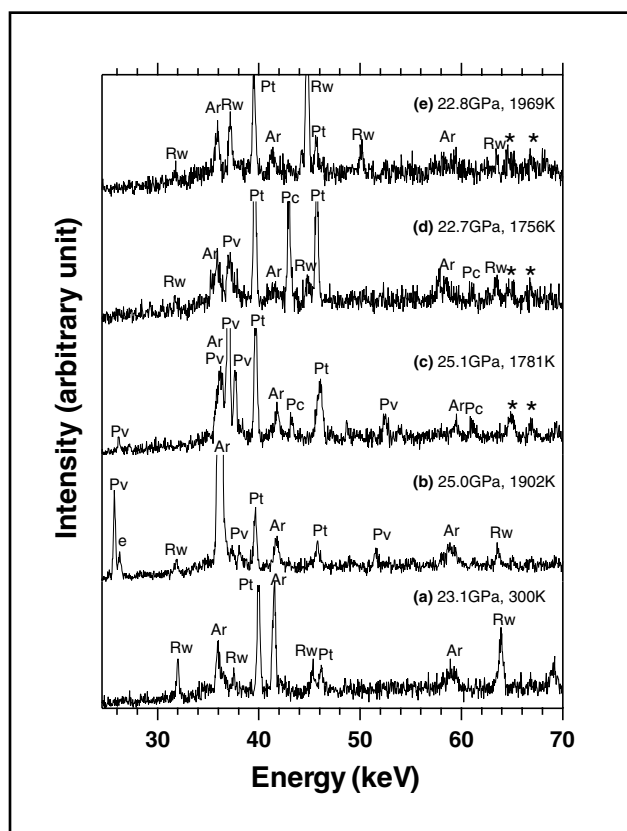


Fig. 2. Representative x-ray diffraction patterns at the indicated pressure-temperature conditions. Rw = ringwoodite form of Mg_2SiO_4 , Pv = MgSiO_3 perovskite, Pc = MgO ; Pt = platinum; Ar = argon; asterisk = platinum fluorescence; e = detector escape peak.

culminating in transformation of a spinel-structured form (ringwoodite) to a mixture of MgSiO_3 (perovskite structure) and MgO (rocksalt structure). The samples were first heated well below or above the expected transition boundary to convert the samples entirely to either ringwoodite or the perovskite mixture. The samples were then heated at conditions ranging from 20 to 35 GPa and temperatures from 1400 K to 2300 K. The samples were probed during heating using energy-dispersive x-ray diffraction and a solid-state detector. The rapid data collection and excellent spatial resolution afforded by this technique are ideal for these experiments, in which the x-ray diffraction patterns of the products and reactants can be readily distinguished. To ensure that data were obtained from a homogeneously heated region, a small ($5 \times 7 \mu\text{m}$), horizontally focused x-ray beam was used, and temperature profiles were repeatedly measured.

Because of the effects of thermal pressure and cell relaxation, the P-T path followed during a given experiment is complex. In a typical sequence of patterns, a ringwoodite sample at 23.1 GPa was heated [Fig. 2(a)]. After 8 min of heating, diagnostic perovskite doublets were observed and the P-T conditions were measured to be 25.0 GPa and 1902 K [Fig. 2(b)]. On the other hand, upon heating ringwoodite near 21 GPa, no transformations were seen. Conversely, beginning with a perovskite mixture [Fig. 2(c)], we observed the appearance of ringwoodite after about 6 min of heating at 22.7 GPa and 1756 K and complete transformation after 24 min [Figs. 2(d) and 2(e)]. On the whole, our observations indicate that the low- and high-pressure phase assemblages coexist at about 23-25 GPa and 1500-2200 K. This scatter is due to temperature uncertainty, preferred orientation, and transition kinetics. Nevertheless, these pressure and temperature conditions are very consistent with those expected to occur at 660-km depth (Fig. 3).

While the present results are based on a relatively simple mineral analog for the Earth's mantle, it is not expected that other chemical constituents will dramatically affect our conclusions. Nevertheless, additional experiments are warranted to investigate more realistic mantle systems, as well as other possible phase transformations that may contribute to this or other seismic discontinuities. Improvements in basic pressure and temperature calibration are also needed. This type of direct study of geological systems at deep-mantle P-T conditions is only just beginning. Nevertheless, it is notable that our results are entirely consistent with recent seismic tomographic studies of three-dimensional mantle structure that appear to show cold subducting slabs penetrating the 660-km

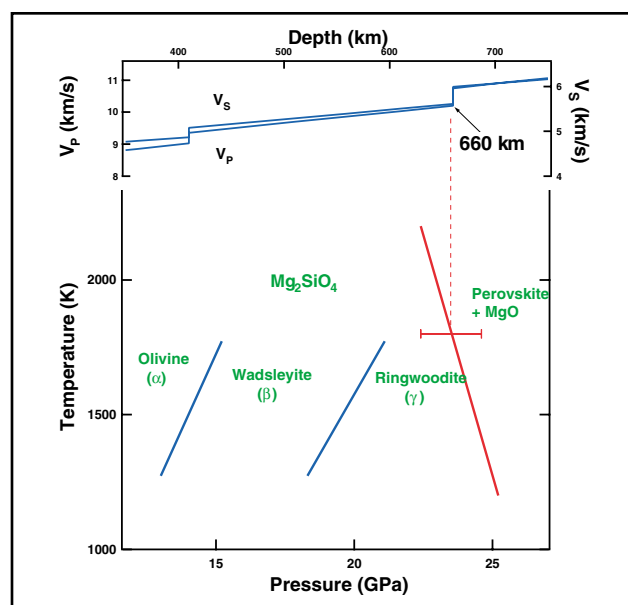


FIG. 3. The top shows compressional (V_p) and shear (V_s) seismic velocities in the Earth's mantle as a function of depth. The bottom shows the experimentally determined locations of phase boundaries in the Mg_2SiO_4 system. Our result for the post-spinel transition is shown by the solid red line (with error bar) which is in excellent agreement with seismic data if the mantle temperature at this depth is ~ 1800 K. This temperature is in agreement with estimates from other geological and geophysical data.

discontinuity into the lower mantle, and thus favor extensive chemical mixing into the deep mantle. Seismic observations of the Earth at very large length scales (~ 1000 km) and laboratory investigations using synchrotron radiation at the microscale (~ 10 μm) are combining to give a consistent picture of deep Earth dynamics.

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S. H. Shim,^{1,*} T. S. Duffy,¹ G. Shen²

¹ Department of Geosciences, Princeton University, Princeton, NJ, U.S.A.

² Consortium for Advanced Radiation Sources, The University of Chicago, Chicago, IL, U.S.A.

* Department of Earth and Planetary Science, University of California, Berkeley, CA, U.S.A.